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During the course of this investigation the following studies were made: Nonlinear optics in atomic vapors, advanced concepts for integrated optics, optical information processing at low light levels, pulse-energy statistics in stimulated Raman scattering, design of off-axis systems, and nonlinear and cooperative effects in Rydberg states. Eleven reports were published during the course of these studies.

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"The Transition from Superfluorescence to Amplified Spontaneous Emission," M. S. Malcuit, J. J. Maki, D. J. Simkin, and R. W. Boyd, Phys. Rev. Lett., 59, 1189, 1987.

"Passive, One-way Correction Using Four-Wave Mixing," K. R. MacDonald, W. R. Tompkin, and R. W. Boyd, in review.

"Rydberg-atom Wave packets Localized in the Angular Variables," John A. Yeazell and C. R. Stroud, Jr., Phys. Rev. A 35, 2806 (1987).

"Transient Theory of Cavity-Modified Spontaneous Emission," Jonathan Parker and C. R. Stroud, Jr., Phys. Rev. A 35, 4226 (1987).

"Bell's Inequalities for Rydberg Atoms," Brian J. Oliver and C. R. Stroud, Jr., J. Opt. Soc. Amer. B 4, 1426 (1987).

"Observation of Spatially Localized Atomic Electron Wave Packets," John A. Yeazell and C. R. Stroud, Jr., in review.

"Above-Threshold Ionization with Femtosecond Pulses: A Comparison of Quantum and Classical Predictions," Jonathan Parker and C. R. Stroud, Jr., in review.

"Transient Absorption by a Rydberg Atom in a Resonant Cavity," Mark Mallalieu, Jonathan Parker and C. R. Stroud, Jr., accepted for publication in Physical Review A.

"Picosecond Excitation of Rydberg Wave Packets" C. R. Stroud, Jr., to appear in Proceedings of Twelfth International Nathigali Summer College in Physics and Contemporary Needs.

"Transients in the Micromaser," C. R. Stroud, Jr., to appear in Proceedings of Twelfth International Nathigali Summer College on Physics and Contemporary Needs.

"Axial approximation in the calculation of the valence bands in semiconductor superlattices," C. Martijn de Sterke and D. G. Hall, submitted for publication.

8. SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT AND DEGREES AWARDED DURING THIS REPORTING PERIOD:

FACULTY	STUDENTS
Robert W. Boyd	Cho, Doo Jin
Dennis G. Hall	deSterke, C. Martijn
G. Michael Morris	Gruhlke, Russel
Michael G. Raymer	Hopler, Mark
John R. Rogers	Koch, Karl
Carlos R. Stroud	Kuo, Shih-jong
Kenneth J. Teegarden	Li, Zheng-Wu
	Lyon, Richard
	Maki, Jeffrey
	Martin, John
	Papademetriou, Stephanos
	Parker, Jonathan
	Wernick, Miles
	Yeazell, John

DEGREE AWARDED:

Michelle S. Malcuit, Ph.D. thesis, "Competition Effects in Nonlinear Optics," University of Rochester, 1987.

Martijn deSterke, Ph.D. thesis, "Contributions to the theory of the electronic and optical properties of Si-Ge_x-Si_{1-x} semiconductor superlattices." University of Rochester, 1987.

M. A. Hopler, M.S. thesis, "Interferometric measurement of refractive index," University of Rochester, 1987.

9. BRIEF OUTLINE OF RESEARCH FINDINGS

A. Nonlinear Optics in Atomic Vapors - Robert W. Boyd

We have made good progress during the past reporting period. Two separate papers were accepted for publication in physical review letters. The abstracts of these papers are reproduced below.

Observation of Deterministic Chaos in a Phase-Conjugate Mirrors

D. J. Gauthier, P. Narum, and R. W. Boyd

Deterministic chaos in the intensity of the beam produced by a barium titanate self-pumped phase-conjugate mirror has been observed. The correlation exponent of the strange attractor is found to depend on the crystal orientation and to lie within the range 1.2 to 2.4, and the order-two Renyi entropy is found to increase with increasing laser intensity and to be as large as 22 bits/sec. A standard model of self-pumped phase conjugation due to four-wave mixing has been generalized to include time dependence. This model predicts frequency shifts and chaotic behavior for the reflectivity.

Transition from Superfluorescence to Amplified Spontaneous Emission

M. S. Malcuit, J. J. Maki, D. J. Simkin, and R. W. Boyd

The cooperative emission process in $KCl:O_2^-$ has been studied as a function of the dephasing rate of the transition dipole. As the temperature of the sample is increased from 10 to 30K, the emission evolves continuously from that characteristic of superfluorescence to that of amplified spontaneous emission. These results are in qualitative agreement with the predictions of current theories, but quantitative agreement is obtained only when current theories are modified so that the noise source that initiates the emission process is allowed to act continuously during the superfluorescent buildup.

In addition, we have developed a new technique for passive, one-way aberration correction. We have written a paper, presently being reviewed, that describes this work. The Abstract of this paper is reproduced below.

Passive, One-way Aberration Correction Using Four-wave Mixing

K. R. MacDonald, W. R. Tompkin, and R. W. Boyd

We have demonstrated a passive method for recovering an optical image that has been degraded by passing through a thin phase-aberrating medium. This method relies on a point source situated near the object of interest to sample the aberration impressed upon the wavefront. Degenerate four-wave mixing in fluoresceine-doped boric-acid glass was used to reconstruct the wavefront.

B. Advanced Concepts for Integrated Optics - Dennis G. Hall

The following is an abstract from a paper that was done which summarizes the work done in the last four months.

Axial approximation in the calculation of the valence bands in semiconductor superlattices

C. Martijn de Sterke

Abstract

We apply the axial approximation, introduced by Altarelli, Ekenberg, and Fasolino [Phys. Rev. **B 32**, 5138 (1985)] to Si-Ge_xSi_{1-x} superlattices and compare the results to exact calculations. In the axial approximation, the warping of the valence bands is neglected so that a cylindrically symmetric system is obtained. We show that the influence of the warping is roughly the same for every semiconductor. According to our calculations, the axial approximation is satisfactorily close to Γ, but at large values of the transverse crystal momentum the warping becomes so severe that the approximation is quite poor. We have also included the warping by treating it as a perturbation applied to the cylindrically symmetric system. This only leads to an improvement when the warping is small.

C. Optical Information Processing at Low Light Levels - G. Michael Morris

1. Pattern Recognition at Low Light Levels

Pattern Recognition using Invariant Features

In our research on invariant filtering the primary emphasis has been on the development of a real-time, automatic machine-vision system. The goal is to develop a system that will perform real-time, automatic identification of objects that appear at unknown positions, scales, or orientations within an incoherently illuminated input scene.

In our method a set of invariant features is computed for each object that is to be identified. (An invariant feature is a numerical quantity that describes the object and remains unchanged when the object is rotated or scaled). When an image is presented to the recognition system, the invariant features of that input image are computed and compared to the features of the reference objects. A similarity measure between the two sets of features is used to make a recognition decision concerning the input object.

The determination of invariant features is a computationally intensive process, and it is generally very difficult to perform such calculations in real time using a digital computer. We have proposed and begun to investigate the use of a position-sensitive photon-counting detection system to implement a Monte-Carlo algorithm for real-time estimation of invariant features.

The Monte-Carlo algorithm for estimating the invariant features of input objects is as follows. First, the location of the object to be identified is determined by using the spatial coordinates of approximately 5000 detected photoevents. Next, invariant features of the input image are computed using the photoevent coordinates. The high-speed generation of the photoevent coordinates, which are used as random variables in the Monte-Carlo algorithm, is what allows the Monte-Carlo estimation of the invariant features to be performed in real time.

Recent work has concentrated on Monte Carlo estimation of complex moment-invariants (moment invariants are a particular type of invariant feature). From a review of the literature, it appears that our hybrid system for computing these complex moment invariants is the first system of any kind to provide accurate, real-time estimates of this type of moment invariant, which is known to be useful for pattern recognition.

Experiments involving moment invariants have been performed. We have used the Monte Carlo technique to compute complex moment-invariants for the images of presidents from U.S. currency. We have found that five-thousand photons provides enough information to distinguish among the images of Lincoln, Washington and Jackson, when they were input to the system at any orientation, and at relative magnifications ranging between 1.0-1.75. In these experiments, the total time needed to detect, process the information, and make a recognition decision is only 50 milliseconds.

We have recently developed analytic expressions for the probability density functions of the moment invariants that are computed using this Monte Carlo approach. This will allow us to make theoretical predictions for the performance of this method for image recognition when the object(s) that are to be recognized are present in a cluttered, noisy environment. We are presently planning to attempt to recognize objects from within such an environment when input to the system is provided by a TV monitor.

A presentation of this work will be given at an upcoming SPIE meeting in Orlando, Florida in April 1988.

D. Pulse-Energy Statistics in Stimulated Raman Scattering - Michael G. Raymer

During the period July 1 - October 31, 1987, we have developed a computer-based, automated data collection system to record two-dimensional images of speckle patterns produced by stimulated Raman scattering (SRS). The system is based on a CCD camera, a frame grabber, and a microcomputer. The problem was made difficult by the need for synchronization with the laser pulses and simultaneous recording of the laser pulse and Stokes pulse energies.

This system, which is operational, will allow us to make the first quantitative measurements of the spatial statistics of SRS. Transverse autocorrelation functions of the SRS intensity will be calculated from the data.

The main scientific question to be addressed is the effect of gain saturation in the SRS process on the spatial statistics. While the total energy of the generated Stokes pulses fluctuates little in the saturated regime, we have found that the spatial pattern continues to fluctuate from shot to shot. This type of saturated speckle pattern is not well understood at this time. Its properties will determine the propagation characteristics of the Stokes beam.

E. Design of Off-Axis System - John R. Rogers

1. Tilted-Component Systems

Background

It was previously reported[1] that the design techniques developed thus far at The Institute of Optics could be used to produce practical designs for unobscured, all-reflective optical systems of moderate optical quality, using only rotationally symmetric surfaces. As an example, an unobscured, all-reflective system was designed which covered a 4° square field with an RMS wavefront error of about one-quarter wave (at .5876 mm) was designed.[2]

Study of the residual aberrations of the above systems reveals two fundamental sources. The first is the fact that the aberrations of third-and higher-orders cannot be simultaneously balanced with a reasonable number of tilted surfaces. The higher-order field aberrations are not overly troublesome at moderate tilt angles (typically, less than about 20°), but larger values of the tilt angles introduce significant amounts of the higher-order aberrations, forcing a trade-off in the design process. The obvious conclusion is that the tilt angles should be kept as small as possible; however, they must be chosen to satisfy the third-order equations and simultaneously uphold the obscuration constraints of the system.

The second fundamental source of aberrations is the trapezoidal, or "keystone" distortion of the incident beam, as it impinges obliquely upon an optical surface. As the aspheric surface departure is rotationally symmetric rather than distorted, this effect introduces a form of aberration peculiar to tilted-component systems. It was suggested at a recent conference that "keystone-distorted aspherics" (that is, one in which the contour lines of aspheric departure have been distorted to match the shape of the incident beam) might be more useful to design than the "anamorphic aspherics" commonly supported by lens design programs.[3]

Recent Achievements:

There is now reason to believe that complex, or "out-of-plane" solutions to the third-order equations of Reference 1 will yield higher-quality optical systems than the plane-symmetric systems studied thus far. The obscuration constraints on a system can clearly be satisfied with smaller tilt angles if the surfaces may be tilted in two directions. It is therefore to be expected that out-of-plane, third-order solutions will be found having lower tilt angles than the current in-plane solutions. Suitable macro routines ("star-commands") were written for the lens design problem.

Evaporative deposition is presently under study as a technique for the production of keystone distorted aspherics. Rotationally symmetric aspherics have been successfully generated. For keystone distorted aspherics, the substrate must be tilted, which requires a large mask-to-substrate separation, which results in a considerable blurring of the mask features, due to the spatial breadth of the source. The spatial intensity distribution of the source has been characterized by measuring the distribution resulting from a step-function mask, differentiating to obtain the slit response function, and inverse Abel transforming to obtain the source distribution. Monte Carlo simulations of the step-function response using this computed source function corroborate the measured step-function. An invited paper on this subject was given at the OSA annual meeting,[4] and a student is preparing a master's thesis in this area.

2. Gradient Index Systems

Background:

Measurement of the index profile of a radial gradient element is made difficult by the requirement that the measurement light path not cross the isoindicial lines of the sample. Of course, measurement of index variation (that is, the index minus the index at the center of the element) can be made by placing a suitably thin sample

into one arm of a Twyman-Green interferometer. The optical path difference of any zone relative to the axis may be found by counting the interference fringes from the center of the interferogram. If both the physical thickness and the optical path lengths are known, the refractive index may be calculated. Unfortunately, the above method gives no information concerning the index at the center of the sample; furthermore, the central index is likely to be altered by the process of creating the gradient. Presently, the method by which the central index is measured is to core-drill out the central part of the sample, pulverize the core, index-match the powdered glass to an oil, and finally measure the index of the oil by conventional means. A measurement accuracy of approximately .001 is achieved by this technique.

Recent achievements

In order to effect a measurement of the index which is non-destructive, quick, and does not probe the sample across the isoindicial lines, an interferometric method has been developed. By placing the sample into one arm of an interferometer and observing not the fringes themselves but the shift of the visibility of the fringes, a measurement of the group refractive index may be made. An interferometer to measure the shift of the visibility curve at several wavelengths has been assembled, and has demonstrated the ability to measure group refractive index to .0005.

The conversion of group index to phase index is fundamentally impossible without apriori information about the material. Fortunately, a study of 215 glasses from the Schott glass catalog has indicated a relationship between the coefficients of the group and phase indices, enabling the measured phase index to be computed from the measured group index. The maximum absolute error in the indices of these 215 glasses was .0013 using this technique. Presently, a paper is under preparation in which approximately 600 glasses from three manufacturers will be used to test the accuracy of this technique, and a master's degree was granted for work in this area.[5]

References:

1. J. R. Rogers, "Vector aberration theory and the design of off-axis systems," SPIE Proc. **554**, pp. 76-81. (1985).
2. J. R. Rogers and S. Tachihara, "Practical tilted mirror systems," SPIE Proc. **679**, pp. 12-16. (1986).
3. J. R. Rogers, "Aberrations of even orders in tilted component systems," presented at the OSA annual meeting, Seattle, WA, (1986).
4. J. R. Rogers, J. D. Martin, and D. A. Smith, "Evaporative deposition of aspheric surfaces," Invited paper, OSA annual meeting, Rochester, NY (1987).
5. M. A. Hopler, "Interferometric measurement of refractive index," masters thesis, University of Rochester, 1987.

F. Nonlinear and Cooperative Effects in Rydberg States - Carlos Stroud

During the past contract period the work on this project was particularly successful. The first experimental production and detection of spatially localized Rydberg electron wave packets was accomplished. An atom was excited into a state in which the electron was localized in a pie-shaped wedge 20° wide and approximately 1μm in radius. The electron was stable in this configuration for the several microseconds required to detect it. This represents the important first step in producing an electron in a state in which a localized wave packet moves in a macroscopic classical orbit. Such an electron will bridge the classical and quantum regimes allowing single atom classical absorption and emission of light.

The progress on this project was reported in 3 journal publications, 3 other papers accepted for publication, and 2 manuscripts under review. In addition 5 oral papers were delivered at national and international conferences, including one invited paper in a plenary session. The titles and abstracts of the manuscripts are reproduced below. They represent an accurate summary of the progress to date.

Rydberg-atom Wave Packets Localized in the Angular Variables

John A. Yeazell, and C. R. Stroud, Jr.

Calculations are presented that show the behavior of a wave packet composed of alkali-metal atom Rydberg states. We demonstrate that it is possible to localize such a wave packet in the polar and azimuthal angles. The evolution of this wave packet is equivalent to the precession of a classical Kepler orbit under the influence of a perturbing potential. In this case, the perturbation is the quantum defect of the alkali-metal atoms. An excitation scheme is proposed for producing these states and the results of numerical model based on this scheme are presented. Finally, the interaction of these angularly localized wave packets with external fields is discussed and a method of detection is suggested.

Transient Theory of Cavity-Modified Spontaneous Emission

Jonathan Parker and C. R. Stroud, Jr.

We present a numerical and analytical study of a multimode Jaynes-Cummings model describing the spontaneous decay of a single atom in a high-Q cavity. The theory of cavity- modified spontaneous emission is discussed in terms of quantities that have clear physical quantities that have clear physical interpretations: the photon wave packet radiated by the atom, its reflection by the

cavity boundaries, and its reabsorption by the atom. Multimode corrections to the single-mode Jaynes-Cummings model are calculated. The multimode corrections are formulated in terms of quantities that may be calculated by solving the single-mode equations of motion.

Bell's Inequalities for Rydberg Atoms

Brian J. Oliver and C. R. Stroud, Jr.

The analogy between two-level atoms and spins is used to show that Rydberg atoms provide a new medium through which Bell's inequalities are replaced by nearly 100% efficient state-selective ionizers in Rydberg-atom experiments. Two methods for producing correlated states of pairs of atoms are discussed. Each method can be used to create correlated states of more than two atoms. A Bell inequality for a three-atom system is considered and compared with quantum-mechanical predictions. A violation of the inequality is predicted.

Observation of Spatially Localized Atomic Electron Wave Packets

John A. Yeazell and C. R. Stroud, Jr.

We have excited and detected an atomic electron wave packet that is localized in the polar and azimuthal angles. The wave packet is formed through the coherent superposition of Rydberg states of atomic sodium. The superposition is achieved by short pulse optical excitation of the atom in the presence of a strong rf field. The wave packet is detected by dc field ionization. The behavior of this wave packet in a strong dc field is much different than that of an eigenstate. This behavior agrees well with a simple classical model.

Transient Absorption by a Rydberg Atom in a Resonant Cavity

Mark Mallalieu, Jonathan Parker and C. R. Stroud, Jr.

A theoretical analysis is presented describing the interaction of the field in a high-Q microwave cavity with an atom that is suddenly excited to the lower of two Rydberg levels that are resonantly coupled by the field. It is found that the field initially in the cavity is canceled by interference with the source field emitted by the atom. The absorption may be characterized as a "darkness wave packet" emitted by the atom and reflected by the cavity walls.

Transients in the Micromaser

C. R. Stroud, Jr.

The Jaynes-Cummings model of a single two-level atom interacting with a single field mode of a lossless cavity is the central problem of quantum optics. In the past 25 years more than a thousand theoretical papers have been written exploring various aspects of this model. Recently an accurate experimental realization of this ideal model has been achieved in the laboratory. The implications of this new experimental capability are discussed, and new experiments are proposed that can explore the transient absorption and emission of a single photon by a single atom in a high-Q cavity.

Picosecond Excitation of Rydberg Wave Packets

C. R. Stroud, Jr.

It is shown that an atomic electron can be prepared in a state closely approximating the classical limit of a localized particle traveling in a Kepler orbit. This state is produced by using a picosecond laser pulse to excite a linear superposition of a closely spaced Rydberg levels. The spatially localized electron wave packet produced has a $\Delta r \Delta p$ uncertainty product which may approach the $\hbar/2$ minimum allowed by Heisenberg's Principle. The possible methods of production of these packets are discussed for localization in the radial coordinate as well as the angular coordinates.

Above-Threshold Ionization with Femtosecond Pulses:

A Comparison of Quantum and Classical Predictions

Jonathan Parker and C. R. Stroud, Jr.

We present numerical solutions of the three-dimensional Schrödinger's and Newton's equations describing a hydrogen atom undergoing above-threshold ionization by an optical femtosecond laser pulse. A clear classical correspondence is found. Various splittings and shifts of the ATI spectral peaks are observed, and are shown to be due to the bound-state structure of the atom.

10. Presentations

"Deterministic Chaos in Phase Conjugate Mirrors," R. W. Boyd, A. L. Gaeta, D. J. Gauthier, and P. Narum, International Workshop on Instabilities, Dynamics, and Chaos in Nonlinear Optical Systems, Il Ciocco, Lucca, Italy, July 9, 1987.

"Cooperation, Competition, and Chaos in Nonlinear Optical Systems," Quantum Optics Seminar, Department of Physics, Imperial College, London, July 29, 1987.*

"Suppression of N-Photon Absorption by the Four-Wave Mixing Process," D. J, Gauthier, M. S. Malcuit, and R. W. Boyd, Fourth International Conference on Multiphoton Processes, Boulder, Colorado, July 13-17, 1987.

"Nonlinear Optical Interactions in Low-Temperature Glasses Containing Organic Dyes," W. R. Tompkin and R. W. Boyd, SPIE Technical Symposium on Optical and Optoelectronic Applied Science and Engineering, San Diego, CA, August 16-21, 1987

"Temporal Instabilities of Spatially Stable Counterpropagating Vector Fields," A. L Gaeta and R. W. Boyd, Fourteenth Congress of the International Commission for Optics, Quebec, August 24-28, 1987.

"Measurements of the Mode Structure of a Phase Conjugate Resonator," M. D. Skeldon and R. W. Boyd. "Strongly Induced Gain and Modified Absorption in a Strongly Driven Sodium Vapor," M. T. Gruneisen, K.R. MacDonald, and R.W. Boyd, "Spatial Evolution of Beam Profiles in an SBS Amplifier," E.J. Miller, M.D. Skeldon, and R. W. Boyd. Optical Society of America, Annual Meeting, Rochester, New York, October 19, 1987.

"Phase Conjugation by Brillouin-Enhanced Four-Wave Mixing," R. W. Boyd, P. Narum, and M. D. Skeldon, International Laser Science Conference, Atlantic - City, New Jersey, November 1-5, 1987. *

"Laser Beam Combining through the Nonlinear Response of a Strongly Driven Atomic Transition," M. T. Gruneisen, K. R. MacDonald, and R. W. Boyd, SPIE Symposium on Innovative Science and Technology, Los Angeles, CA January 10-15, 1988.*

"Use of Balanced Homodyne Detectors for Tests of Bell's Inequality," B. J. Oliver and C. R. Stroud, Jr., Optical Society of America, Annual Meeting, Rochester, NY, October, 1987.

"Quantum vs. Classical in Above-Threshold Ionization, Jonathan Parker and C. R. Stroud, Jr., Optical Society of America, Annual Meeting, Rochester, NY, October, 1987.

"Spatially Localized Rydberg Atom Wave Packets," John A. Yeazell, Optical Society of America, Annual Meeting, Rochester, NY, October, 1987.

"Comparison of Classical and Quantum Theories of ATI," Jonathan Parker and C. R. Stroud, Jr., International Conference on Multiphoton Processes, Boulder, CO, July, 1987.

"Optical Tests of Quantum Theory," C. R. Stroud, Jr., Plenary Invited Lecture, International Conference on Lasers '87, Lake Tahoe, NV, December 1987.*

"Evaporative deposition of aspheric surfaces," J. R. Rogers, J. D. Martin, and D. A. Smith, OSA annual meeting, Rochester, NY (1987).*

* Invited Paper